ION BASED HIGH-TEMPERATURE PRESSURE SENSOR

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ABSTRACT

A high speed, durable, ion probe based pressure sensor is being investigated for use in pulse detonation engines. The environment encountered in such engines necessitates high temperature and durable (vibration resistant) devices. Traditional pressure sensors can be used, however thermal insulating materials must be used to protect the diaphragm. These materials dampen and reduce the pressure wave allowing for qualitative results only. An alternative pressure sensing method is investigated for pressures behind a hydrocarbon flame in the pulse detonation engine. Hydrocarbon flames generate ions that are quenched by collisions with other species and walls. As the collision rate is a function of pressure, so too is the ion quench rate. The ion decay rate is measured using an ion probe well suited for the high temperature flow, inexpensive, and has no moving parts. Similar systems have been used to determine equivalence ratio in automobile engines. Further, wave speed may be determined through the use of multiple sensors. This investigation builds upon these capabilities to examine the quantitative pressures. In the current design, the ion probe acts as a charged capacitor. When an ionized field nears the probe, the electrical circuit is connected. The electrode on the probe discharges through the ionized field to a grounded plate. The rate of discharge indicates the strength of the ionized field which decays according to pressure. The experimental setup for this investigation and preliminary findings are presented here. Correlations between the decay rate and pressure are to be determined and compared to theory.

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INTRODUCTION

The United States Air Force, along with other organizations, is currently investigating the Pulse Detonation Engine (PDE) as a future propulsion system. While not a new concept, the engine is still in developmental stages. The PDE theoretically offers a higher efficiency with less complexity and lower weight than the turbofans in use today. The PDE is also attractive due to its large flight envelope: from static up to around Mach 5.

The basis for the PDE is the higher efficiency of a detonation combustion process compared to the deflagration process used in conventional turbomachinery based air-breathing engines of today. This efficiency comes from the near constant volume process and the fact that the PDE does not require the working fluid to be compressed prior to heat addition. Simple theoretical calculations show the efficiency of the Brayton, Humphrey, and Chapman-Jouguet Detonation cycles to be 27%, 47%, and 49% respectively.[1] In addition to the clear thermodynamic advantages, the PDE also has the potential to reduce cost and enhance performance without the heavy turbomachinery in conventional air-breathing engines.

Despite recent progress, significant challenges remain before reliable operation with practical fuels is realized.[2] Further, the cycle creates higher temperatures than the Brayton cycle leading to high heat loading.[3] These high temperatures limit the diagnostic tools available to researchers. Specifically, conventional piezoelectric based pressure transducers are ill-suited for the high temperatures, and harsh vibrational environment within the PDE. Protective ablative coatings on the pressure transducers improve the resistance to the harsh environment but reduce the sensitivity. These coatings reduce the effectiveness of the pressure transducer as a quantitative instrument because of the inherent damping of the materials. Accurate compensation for the damping effects is not feasible due to the variability in the thickness of the material as well as the ablation rate itself. A durable, quick response quantitative pressure sensor is needed to optimize the PDE during development, and also to provide feedback for engine control.

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BACKGROUND

It is well known that hydrocarbon flames have conductive properties. Considerable research over several decades has investigated the formation of ions in flames.[4] The formation of these ions within the flame is attributed to the chemi-ionization reactions.[5] One important example being:[6]

$$CH + O \rightarrow CHO^+ + e^- \tag{1}$$

However, the local thermal equilibrium concentration as a function of temperature is given by the Saha equation:

$$\frac{n_i n_e}{n_{i-1}} = 2\left(\frac{2\pi m_e kT}{h^2}\right)^{\frac{1}{2}} \frac{B_i}{B_{i-1}} \exp\left[-\frac{E_{ion}}{kT}\right] \tag{2}$$

The reaction in Eq. (1), as occurs in a hydrocarbon flame, places the ion concentration at super-equilibrium levels. The net rate change of ion concentration will of course be the difference between the production and recombination rates of reaction. As the recombination reaction has a molecularity of two, the rate of decay is therefore dependent on the square of pressure. A typical recombination reaction is given by:[6]

$$\begin{aligned} H_2O^+ + e^- &\rightarrow H_2O + H \\ &\rightarrow OH + 2H \end{aligned} \tag{3}$$

By measuring the ion density as a function of time it is possible to determine the pressure. This measurement is simplified if the decay is observed well past the ion generating reaction front so that only the recombination reaction rate need be considered.

These chemi-ionization relationships have already successfully measured various properties of combustion. Complex probes are not required; a device as simple as a standard internal combustion engine spark plug can provide a great deal of information about the combustion process. In recent years, the spark plug has been used as a diagnostic tool to measure the equivalence ratio, knock, misfire and is even used as a feedback sensor for ignition control.[7-11] These methods apply a constant DC voltage across the sparkplug causing it to act as a capacitor. When the spark is not occurring, the ionization can be measured as a current across the gap.

Similar methods along with Gaussian-shaped functions were used to approximate the pressure decay from a maximum peak pressure.[7] Saitzkoff et. al., investigated the use of the spark plug to measure pressure for internal combustion engines and derived a theoretical model that showed good correlation to actual pressures in high load engine conditions. The normalized current and pressure values were related by the following:[12]

$$\frac{I}{I_{\max}} = \frac{1}{\left(\frac{P}{P_{\max}}\right)^{\frac{1}{2}-\frac{3}{4}\frac{\gamma-1}{\gamma}}} \exp\left[-\frac{E_i}{2kT_{\max}}\left(\left(\frac{1}{\left(\frac{P}{P_{\max}}\right)^{\frac{\gamma-1}{\gamma}}}\right)-1\right)\right] \tag{3}$$

Unlike the flame region where quick chemi-ionization reactions dominate the ion production, the post-flame region is dominated by the slow forming Nitric Oxide (NO).[12] Calculated pressures were correlated to the post-flame ionization peak due to NO production.[12] NO is formed by means of the extended Zeldovich mechanism.[12]

$$O + N_2 \leftrightarrow NO + N \tag{4}$$
$$N + O_2 \leftrightarrow NO + O \tag{5}$$
$$N + OH \leftrightarrow NO + H \tag{6}$$

NO is also formed by the low temperature "prompt" or Fenimore NO_x mechanism. This finding that NO dominates the ion current in the post flame region seems to contradict much of the theory and experimental work in chemi-ionization.[4-6] In actuality, this model is only applicable to high engine loads where higher, longer duration temperatures and pressures exist.[13] These conditions provide the necessary activation energy and time to complete the slow chemical kinetic processes to create NO. Although the characteristic times are comparable, the pressures in the PDE, near 5 atm, are considerably lower than the 10-20 atm for an IC engine. Therefore it is expected that the second peak of ion concentration will not be observed in the PDE.

In order to broaden the spectrum of the model, it must be known if the charged particles are dominated by the electric field in the form of the drift velocity or dominated by the temperature of the gas.[13] Under many circumstances both the electric field and the temperature must be taken into account.[13] This method is complicated by the fact that the ionization depends upon the thermodynamic state that the sensor is trying to detect.[15] Therefore additional information and/or assumptions are required to correct the problem.[13]

For detonation waves, the shock has little influence on the ionization compared to the flame or the detonation wave.[14] In a mixture of $H_2 + O_2$ the conductivity was found to be 4.5 X 10^{-4} and 4 X 10^{-5} (ohm cm)$^{-1}$ for the

detonation and flames respectively.[14] Conversely, the shock conductivity was several orders of magnitude lower at 5.4 X 10^{-13} (ohm cm)$^{-1}$.[14] Therefore the generation of ions by the shock can be considered negligible.

Applied to the PDE, the spark plug acts as a rugged ion sensor to measure wave speed.[15,16] The measurement is made by determining the time delay between the voltage discharges of two spark plugs a known distance apart in the detonation tube.[15,16] Extending the use of the spark plug to measure pressure is a logical improvement. Before this can extension can be put to use, the underlying theory must be tested and engineering challenges overcome.

EXPERIMENTAL APPROACH

The spark plug was selected as an ion sensor because of the proven use in IC engines, the inherent durability to the harsh PDE environment, no moving parts and low cost.

Since this is a work in progress, the experiment setup is also in progress. However, the experiment will test the theory in a constant volume combustion bomb. Results are expected to be similar to those already conducted for internal combustion engines, although without the complexity of the second ion peak due to NO_x generation. Since the constant volume process is a close approximation to the PDE, the results should also be similar to those of the actual PDE cycle. Methane will be used as a fuel due to ease of use and relatively simple reaction process compared to heavy hydrocarbons.

The experiment was built around a 1/2 liter pressure vessel with several instrument ports in the lid as shown in Figure 1 and Attachment 1. The ports are connected to a source of methane, a source of dry high pressure air, a vacuum pump, and an exhaust vent that control the equivalence ratio by partial pressures. A conventional Omega PX303 pressure transducer fixed to another port will correlate the results of the ion sensor. A K-type thermocouple partially inserted into the vessel through another port determines the average temperature in the vessel. A band heater on the outside of the vessel near the base produces a buoyancy effect to encourage the proper mixing of the air and methane.

The mixture is ignited using a traditional spark plug connected to an ignition coil. A low DC voltage is applied across the ion sensor, a Champion RC12LYC spark plug, to energize it as a capacitor. A Keithley 6487 picoammeter and integrated voltage-source is used to directly measure the current through the sensor.

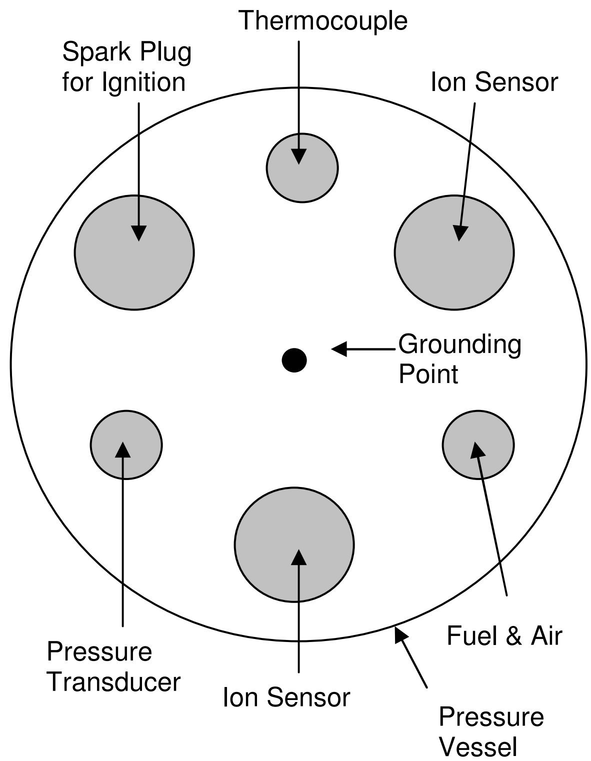

Figure 1 - Top View of Combustion showing 6 instrument ports and grounding point.

The outputs of all sensors except for the ion sensor, are conditioned with appropriate National Instruments (NI) SCXI components which are in turn connected to a 12-bit NI 6024E data acquisition card (DAC) as shown in Figure 2.

The current of the ion sensor is outputted from the picoammeter and captured by a 5 megasample per second 12-bit NI 6110 DAC. These inputs are

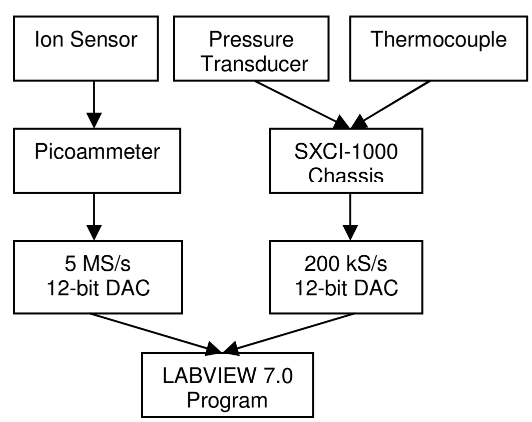

Figure 2 - Experiment data flow from sensors to LabView.

controlled through a LabView program and hardware timed for accurate event timing.

This experiment will be conducted by varying several initial conditions. Tests will be conducted at equivalence ratios of 0.7, 1.0, & 1.2. Initial pressures will range from 0.5 atm to 5 atm. Initial temperatures will near or slight above ambient.

The results will then be post-processed to determine how accurately the ion sensor can predict the pressure. Based on the results, the ion sensor will then be tested in the Air Force Research Lab pulse detonation engine facility.

RESULTS AND CONCLUSIONS

Because the ion current is influenced by electric fields, careful consideration must be given to ensure proper shielding. Voltage sources can skew the results and introduce erroneous fluctuations in the measurements. The ion sensor is particularly sensitive because of the low current being measured. The conventional pressure transducer is less susceptible because the noise is lower than the accuracy of the transducer and the limitations of the 12-bit DAC. The thermocouple is also more resistant to noise because of filtering built into the SCXI-1112 module connected to the SCXI-1000 chassis. In order to reduce noise, with 60 Hz being the dominate source, all the ion sensor cables were shielded and properly grounded. This shielding helped lower the noise by nearly 10 dB.

In applying the spark plug as a pressure sensor to the PDE, several differences from the internal combustion engine must be taken into account. The sensor will only be useful in areas of relatively high ionization since low levels are very susceptible to noise and other influencing factors. Further, the generation of the ions is a complicated process that is difficult to predict because of the multiple interactions. The decay of the ions is a more predictable function of temperature and, most importantly, pressure. The spark plug will only be used to measure the pressure in regions that are dominated by ion decay because of the unknowns involved in ion generation. These limitations in the sensor's useful environment are not severe for the PDE because of the well defined regions in wave structure. For the PDE, the spark plug can measure the pressure in the post-combustion zone. At this point, the ionization should decrease from the peak of chemi-ionization. However, another ionization peak in the post-combustion region is possible due to the slower production of NO but not expected in the PDE. While the sensor can be used to measure the ion decay from either peak, the generation of NO can skew results if measuring the ion decay from the chemi-ionization peak.

Pressure is measured as a function of the ion decay from a relative peak so real time operation is not possible. Only during post-processing can the peak be located. These near real time calculations should be quick enough to describe each detonation cycle. In the future, the spark plug could also be used as feedback for engine controls similar to methods developed for IC engines.

Although the spark plug has been employed to measure pressure in internal combustion engines, several engineering challenges remain before it can successfully be employed in the PDE.

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Attachment 1 – Experiment Setup